

Brushing Number and Zero-Forcing Number of Graphs and their Line Graphs

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Abstract

In this paper we compare the brushing number of a graph with the zero-forcing number of its line graph. We prove that the zero-forcing number of the line graph is an upper bound for the brushing number by constructing a brush configuration based on a zero-forcing set for the line graph. Using a similar construction, we also prove the conjecture that the zero-forcing number of a graph is no more than the zero-forcing number of its line graph; moreover we prove that the brushing number of a graph is no more than the brushing number of its line graph. All three bounds are shown to be tight.

Keywords: zero-forcing number, brushing number, line graph

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1 Introduction

Recently there has been much research on different edge and node search algorithms for graphs, typically based on different applications and modelling of different situations. Each variation leads to new graph parameters and it is interesting to compare these different parameters, particularly where the parameters have different motivations. For example, in [8] it is proven that the zero-forcing number of a graph is equal to the fast-mixed search number and in [9] a connection between the imbalance of a graph and brushing is established.

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In this paper we compare the zero-forcing number and the brushing number of a graph. All the graphs that we consider are simple graphs, meaning no graph has a loop or multiple edges.

To introduce the zero-forcing number of a graph G , we begin with a colouring of the vertices of G with the colours black and white. A black vertex can *force* a white vertex to change its colour to black according to a colour-changing rule: if v is black and w is a white neighbour of v , then v can force w to become black only if w is the only white vertex that is adjacent to v . A set of vertices in a graph is a *zero-forcing set* for the graph if, when the vertices in this set are initially set to black and the colour-changing rule is applied repeatedly, all the vertices of the graph are eventually forced to black. The *zero-forcing number* of a graph G is the size of the smallest zero-forcing set for the graph and is denoted by $Z(G)$. For additional background on zero forcing for graphs, see [1, 3, 4, 10].

The brushing number of a graph is motivated by a variant of graph searching. The variation we consider here was introduced in [11] and explored in more detail in [5] and [13]. Specifically, we start with a graph G that models a situation of contamination, meaning that initially every edge and every vertex is deemed to be *dirty*. Cleaning agents called *brushes* are placed at some of the vertices (this is the *initial configuration* of brushes) and there is a process by which the edges and vertices are subsequently *cleaned*. Drawing terminology from the realm of chip firing, a single vertex *fires* at each step in this process. A vertex v is permitted to fire only if the number of brushes at v at the time that it fires is at least the degree of v (that is, the degree in the graph as it is at the time). When a vertex v fires, the brushes on v clean v , and at least one unique brush traverses each edge incident with v , thereby cleaning the dirty edges that were incident with v . At the end of the step each brush from v is placed at the vertex adjacent to v at the endpoint of the edge it traversed (excess brushes are allowed to remain at v , although they then cease to have any future role). The vertex v and all of its incident edges (which are now clean) are removed from the graph and the process continues (instead of removing them from the graph one can alternatively represent the clean edges by dashed lines, and the clean vertices as hollow circles). The process is complete when there are no vertices that can fire. Any edges or vertices that survive all remain dirty, so if the remaining graph is empty then the initial configuration was capable of cleaning the original graph.

The *brushing number* of a graph is the minimum number of brushes needed for some initial configuration to clean the graph. For a graph G , this is denoted by $B(G)$. There are several variants of this parameter; here and in [5] edges are allowed to be traversed by more than one brush, and each edge is traversed during at most one step of the cleaning process. Alternatively we could require that each edge is traversed by only one brush; the number of brushes required in this scenario is denoted by $b(G)$ and was studied in [2] and [12]. It is clear that a brushing strategy with this restriction is also a brushing strategy in our setting, so for any graph G it holds that $B(G) \leq b(G)$. It was shown in [9] that $b(G)$ is equal to half of the minimum total imbalance of the graph G , which in turn led to a proof that shows that $b(G)$ is \mathcal{NP} -hard.

To demonstrate these definitions, we will give the value of both $Z(G)$ and $B(G)$ for some well-known graphs. As is usual, K_n denotes the complete graph on n vertices, C_n is the cycle on n vertices, P_n is the path with n vertices and $K_{m,n}$ is the complete bipartite graph; in particular, $K_{1,n}$ is the star with n edges.

Proposition 1.1. For $n \geq 3$

$$(i) \ B(K_n) = \left\lfloor \frac{n^2}{4} \right\rfloor \text{ (see [5]),}$$

$$(ii) \ Z(K_n) = n - 1,$$

$$(iii) \ B(K_{1,n}) = \lceil n/2 \rceil \text{ (see [11]),}$$

$$(iv) \ Z(K_{1,n}) = n - 1,$$

$$(v) \ B(P_n) = Z(P_n) = 1,$$

$$(vi) \ B(C_n) = Z(C_n) = 2.$$

The first two statements show that $B(K_n) > Z(K_n)$ for $n \geq 4$. Moreover, by taking n sufficiently large, $B(K_n) - Z(K_n)$ can be made arbitrarily large. Conversely, the next two statements show that $B(K_{1,n}) < Z(K_{1,n})$ for $n \geq 4$; and by taking n sufficiently large $Z(K_{1,n}) - B(K_{1,n})$ can be made arbitrarily large. This confirms that when considering the brushing number and the zero-forcing number of the same graph we should not be trying to bound one by the other. In the brushing process the brushes traverse each edge, so rather than comparing the brushing number of a graph to the zero-forcing number of the graph, we compare the brushing number to the zero-forcing number of the line graph. For a graph G define the *line graph* of G , denoted by $L(G)$, to be the graph with a vertex for each edge of G where two of these vertices in $L(G)$ are adjacent if and only if the corresponding edges are incident in G . If we label the vertices of G by v_i , then the vertices of $L(G)$ can be labelled by the edges $\{v_i, v_j\}$ of G . If two distinct vertices of $L(G)$, say $v = \{v_i, v_j\}$ and $w = \{w_i, w_j\}$, are adjacent in $L(G)$, then $v \cap w$ is non-empty (it is exactly the vertex in G that is on both edges).

The cycle C_n is unusual in terms of its line graph, since it is the only connected graph that is isomorphic to its own line graph. So Proposition 1.1 implies that for $n \geq 3$

$$B(C_n) = B(L(C_n)) = 2 = Z(C_n) = Z(L(C_n)).$$

In this paper we explore how the parameters $B(G)$, $B(L(G))$, $Z(G)$ and $Z(L(G))$ are related to one another more generally. In Theorem 3.1 we prove that $B(G) \leq Z(L(G))$, and in Corollary 3.3 it is further established that $B(G) \leq b(G) \leq Z(L(G))$. The example of the cycle shows that these bounds cannot be improved (these bounds are also tight for the path P_n on $n \geq 2$ vertices).

The line graph of the complete graph K_n is the Johnson graph $J(n, 2)$. In [7], it is shown that the zero-forcing number of $J(n, 2)$ is $\binom{n}{2}$, and thus for $n \geq 3$

$$B(K_n) = \left\lfloor \frac{n^2}{4} \right\rfloor < \binom{n}{2} = Z(L(K_n)). \quad (1)$$

So not only can the inequality $B(G) \leq Z(L(G))$ be strict, but the difference can be arbitrarily large. Further, for $n \geq 4$

$$B(K_{1,n}) = \lceil n/2 \rceil < n - 1 = Z(K_n) = Z(L(K_{1,n})) \quad (2)$$

which shows that even for trees the difference between the brushing number and the zero-forcing number can be arbitrarily large.

In [6] it is proved that $Z(G) \leq 2Z(L(G))$ for any non-trivial graph G . Moreover, it is proved that $Z(G) \leq Z(L(G))$ when G is a tree or when G contains a Hamiltonian path and has a certain number of edges, and it is conjectured that $Z(G) \leq Z(L(G))$ for any non-trivial graph G . Using a refinement of our proof that $B(G) \leq Z(L(G))$, in Theorem 4.1 we prove this conjecture. With Theorem 5.1 we also prove that $B(G) \leq B(L(G))$ for any non-trivial graph. The example of the cycle shows that these bounds are tight.

2 Some Preliminaries

Before proving our main results we make some observations and set some notation that will be used throughout this paper. It is not hard to see that the zero-forcing number (resp. the brushing number) of a graph is the sum of the number on the components of the graph. Throughout this paper we primarily consider connected graphs, but the results may be extended to disconnected graphs. Also we do not consider the connected graph that is only a single vertex, since the line graph of this graph is the empty graph. Note that if G is connected, then $L(G)$ is also connected.

Computing the zero-forcing number for graphs is an \mathcal{NP} -hard problem (see Theorem 3.1 in [8] and Theorems 6.3, 6.5, Corollary 6.6 in [15]). The zero-forcing number and the brushing number are not minor monotone [4]: the operations of edge-deletion and edge-contraction may either increase, decrease or not change either of the zero-forcing number and the brushing number of a graph.

At each step in a zero-forcing process, one vertex v forces exactly one other vertex, say w , to become black; moreover, w is the only vertex that v is capable of forcing. So the vertices of a graph G can be arranged into $Z(G)$ oriented paths \mathcal{P}_i – these paths are called *zero-forcing chains*. The first vertex in \mathcal{P}_i is a vertex in the zero-forcing set (so it is initially coloured black) and a vertex v is immediately followed by w in \mathcal{P}_i if and only if v forces w . Observe that these paths are disjoint induced paths in G ; if a vertex never forces another vertex and is never forced, then it is the single vertex in a path of length 1.

If the vertex v forces w , we write $v \rightarrow w$. If Z is a zero-forcing set for $L(G)$, then the zero-forcing chains for Z comprise a set of $|Z|$ induced paths in $L(G)$. We denote these paths by

$$\begin{aligned} \mathcal{P}_1 &= w_{1,1} \rightarrow w_{1,2} \rightarrow \cdots \rightarrow w_{1,f(1)}, \\ \mathcal{P}_2 &= w_{2,1} \rightarrow w_{2,2} \rightarrow \cdots \rightarrow w_{2,f(2)}, \\ &\vdots \\ \mathcal{P}_{|Z|} &= w_{|Z|,1} \rightarrow w_{|Z|,2} \rightarrow \cdots \rightarrow w_{|Z|,f(|Z|)}, \end{aligned} \tag{3}$$

where f is a function from $\{1, \dots, |Z|\}$ to \mathbb{Z}^+ . In the zero-forcing process, $w_{i,j}$ forces $w_{i,j+1}$ (and this is the only vertex that $w_{i,j}$ forces). Further, we will assume that the first time a vertex forces another vertex in the process is when $w_{1,1}$ forces $w_{1,2}$.

At the step in the zero-forcing process when $w_{i,j}$ forces $w_{i,j+1}$, we say that $w_{i,j}$ is the *active vertex*. Each vertex may perform at most one force, after which we say it is *used*. If $w_{i,j}$ is an active vertex at some step, then $w_{i,j+1}$ is its only white neighbour. Thus if $w_{i,j}$ is adjacent to a vertex in another path, then the vertex in the other path must be black at the time that $w_{i,j}$ is active.

The *brushing process* or *strategy* for a graph describes how the brushes move through the graph, which can also be described by listing the vertices in the order in which they fire (along with details of how vertices with more brushes than incident dirty edges distribute their excess brushes upon firing). Following the route of a brush through this process would give a directed path in G , but unlike zero-forcing chains these paths are neither induced nor disjoint.

3 Brushing number of a graph vs. the zero-forcing number of its line graph

In this section we show that the seemingly unrelated concepts of zero-forcing and brushing are in fact linked to one another. Specifically we prove that the brushing number of a graph is bounded by the zero-forcing number of its line graph.

Theorem 3.1. *For any graph G with no isolated vertices, $B(G) \leq Z(L(G))$.*

Proof. We may assume that G is connected. Let Z be a zero-forcing set for $L(G)$ and let $\mathcal{P}_1, \dots, \mathcal{P}_{|Z|}$ be the zero-forcing chains for Z . Note that for each chain \mathcal{P}_i , the first vertex in the chain, namely $w_{i,1}$, is in Z .

To prove the theorem, we will describe a brush configuration and a strategy for brushing G with at most $|Z|$ brushes. For each path \mathcal{P}_i , we will assign a brush to a vertex in G . These brushes will be assigned to one of the endpoints of the first edge in the path, carefully determining which endpoint to use at each stage.

Initially, we can assume without loss of generality that at the first step in the zero-forcing process $w_{1,1} = \{a, b\}$ forces $w_{1,2} = \{b, c\}$. We assign the brush for \mathcal{P}_1 to the vertex in G that is on the edge $w_{1,1}$ but not on $w_{1,2}$, namely the vertex $w_{1,1} \setminus w_{1,2} = a$. Next, for $i \geq 2$, we add a brush to the vertex $w_{i,1} \cap w_{i-1,1}$ in G for each path \mathcal{P}_i for which the initial vertex $w_{i,1}$ is adjacent to $w_{i-1,1}$. Once this brush has been added, we say that \mathcal{P}_i has been *used*.

At this point the vertex a in G can fire; the brush from \mathcal{P}_1 is sent to b , while for every other vertex adjacent to a there has been a brush placed at a .

Now we move to the first step in the zero-forcing process: the vertex $w_{1,1} = \{a, b\}$ forces $w_{1,2} = \{b, c\}$. There is one brush on b (the one from \mathcal{P}_1 initially placed on a) – this brush will be sent down edge $w_{1,2}$. At this point vertex b in G can fire because before a fires there has been a brush placed at b corresponding to each unclean edge at b , except for the edges $w_{1,1}$ and $w_{1,2}$; and the firing of a decreases the number of unclean edges at b by one while the number of brushes at b increases by one.

We now move to the next step of the zero-forcing process, at which the active vertex $w_{i,j} = \{d, e\}$ forces $w_{i,j+1} = \{e, f\}$ (and at this stage $w_{i,j+1}$ is the only white neighbour of $w_{i,j}$). If $w_{i,j}$ is adjacent to a vertex that is the head of a path \mathcal{P}_k that has not been used, say vertex $w_{k,1}$, then a brush is added to the vertex $w_{i,j} \cap w_{k,1}$, and we mark \mathcal{P}_k as used. Then in G the vertex $d = w_{i,j} \setminus w_{i,j+1}$ (the vertex on $w_{i,j}$ that is not on $w_{i,j+1}$) can fire, if it has not fired before, and send a brush along edge $w_{i,j}$. This is because for any black vertex $w_{\ell,m} = \{d, g\}$ in $L(G)$ adjacent to $w_{i,j} = \{d, e\}$ that is not the head of a path that has not been used it must be true that g has already fired and cleaned the edge $w_{\ell,m} = \{d, g\}$.

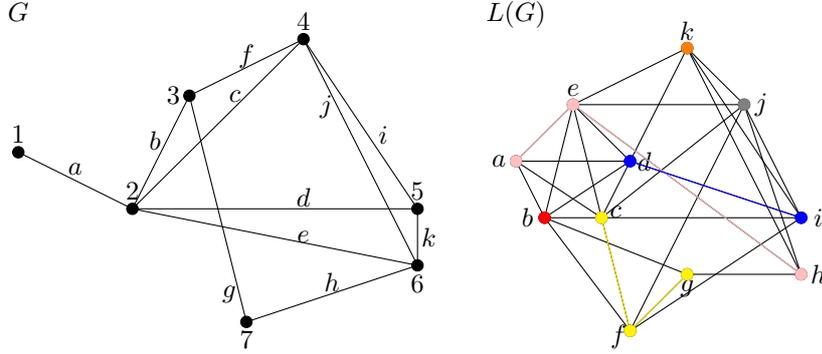


Figure 1: Zero-forcing chains for $L(G)$

in G while sending a brush to d . In the case that $w_{i,j+1} = \{e, f\}$ is the final vertex in the forcing chain \mathcal{P}_i , then a similar argument shows that e can fire in G and then f can fire.

Continue like this for every step of the zero-forcing process. If there are any unused paths left then these paths must contain only a single vertex, which is initially black. If $w = \{v_1, v_2\}$ is such a vertex of $L(G)$ (where v_1 and v_2 are vertices of G) then add a brush to v_1 . For any other vertex $w_{k,1}$ that is adjacent to w such that $\mathcal{P}_k = w_{k,1}$ is an unused path, add a brush to $w \cap w_{k,1}$. Now the vertex v_1 in G can fire, followed by v_2 . Continue like this until all the paths of length 1 are used.

Since G is connected, this process will clean all edges of G , and any vertex v of G that is left unclean can fire because there is necessarily a clean edge at v (therefore at least one brush), but no unclean edges. Clearly with this assignment the number of brushes used is equal to the number of paths $|Z|$. \square

To illustrate the brushing strategy, we give a detailed example. Consider the graph G and its line graph $L(G)$ (see Figure 1). The set $\{b, g, h, i, j, k\}$ is a zero-forcing set in $L(G)$ (so b, g, h, i, j, k are all initially black vertices in $L(G)$) and the zero-forcing chains are below (and are drawn in Figure 1).

$$\mathcal{P}_1 = g \rightarrow f \rightarrow c, \quad \mathcal{P}_2 = i \rightarrow d, \quad \mathcal{P}_3 = h \rightarrow e \rightarrow a, \quad \mathcal{P}_4 = b, \quad \mathcal{P}_5 = k, \quad \mathcal{P}_6 = j$$

For this example, there are 11 steps in the brushing strategy. These are given below and there is a diagram of the graph for each step in Figure 2. In the diagram the brushes are represented with a $*$ at the vertex, and at each step where a new brush is introduced, we put a circle around the new brush.

- (1) In the first step of the zero-forcing process on $L(G)$ g zero forces f . Following our brushing strategy in G we put two brushes at 7 (corresponding to the initially black vertices g and h in $L(G)$).
- (2) Vertex 7 fires.
- (3) Add a new brush to vertex 3 (corresponding to the initially black vertex b).
- (4) Vertex 3 fires. One brush is moved to 2 along b , cleaning b ; one brush is moved to 4 along f , cleaning f .

- (5) In the next step in the zero-forcing process on $L(G)$ edge f forces c . Following our brushing strategy in G we put two brushes at 4 (corresponding to the initially black vertices i and j in $L(G)$).
- (6) Vertex 4 fires; one brush is moved to 2 along c , cleaning c ; one brush is moved to 5 along i , cleaning i ; one brush is moved to 6 along j , cleaning j .
- (7) In the next step in the zero-forcing process i forces d . In G , edge i is already clean. In order to clean d in G following our brushing strategy, we put one brush at 5 (corresponding to the initially black vertex k in $L(G)$).
- (8) Vertex 5 fires since there are two brushes at 5 and two unclean edges incident with it, namely d and k . One brush is moved to 2 along d , cleaning d ; one brush is moved to 6 along k , cleaning k .
- (9) In the zero-forcing process in $L(G)$ vertex h forces e . In G , edge h has already been cleaned at some earlier step, and so at 6 no new brushes are added. Vertex 6 fires and cleans e .
- (10) Finally, in $L(G)$, vertex e forces a . In G , e has been cleaned in the previous step, and so no brushes are added. Vertex 2 fires and cleans a .
- (11) Finally, vertex 1 fires.

Theorem 3.1 is stated for graphs without isolated vertices. Adding an isolated vertex to a graph increases the brushing number by one, since one brush must be placed on the isolated vertex to clean it. However adding an isolated vertex to a graph does not change the line graph. So it is easy to see that the following corollary holds.

Corollary 3.2. *For any graph G with k isolated vertices, $B(G) \leq Z(L(G)) + k$.*

Recall that $b(G)$ is defined to be the minimum number of brushes needed to clean all edges and vertices of G where each time a vertex fires only one brush is allowed to be moved along each incident edge. It is not difficult to observe that the brushing strategy given in the proof of Theorem 3.1 never requires more than one brush to be moved along an edge in G . This observation results in the following corollary to Theorem 3.1.

Corollary 3.3. *For any graph G with no isolated vertices, $B(G) \leq b(G) \leq Z(L(G))$.*

Similar to Corollary 3.2, we also get the following result.

Corollary 3.4. *For any graph G with k isolated vertices, $B(G) \leq b(G) \leq Z(L(G)) + k$.*

We note that often the strategy described in Theorem 3.1 provides a brushing of G that could sometimes use strictly less than $Z(L(G))$ brushes (by adding a brush to a vertex at some step in the brushing procedure only if it is necessary to do so to make the vertex fire). However, the brushing strategy in Theorem 3.1 does not give a clear insight on how small $B(G)$ can be compared to $Z(L(G))$, nor on the problem of characterizing the graphs G for which $B(G) = Z(L(G))$. We note that equality holds for cycles and paths. Furthermore by Equation 1,

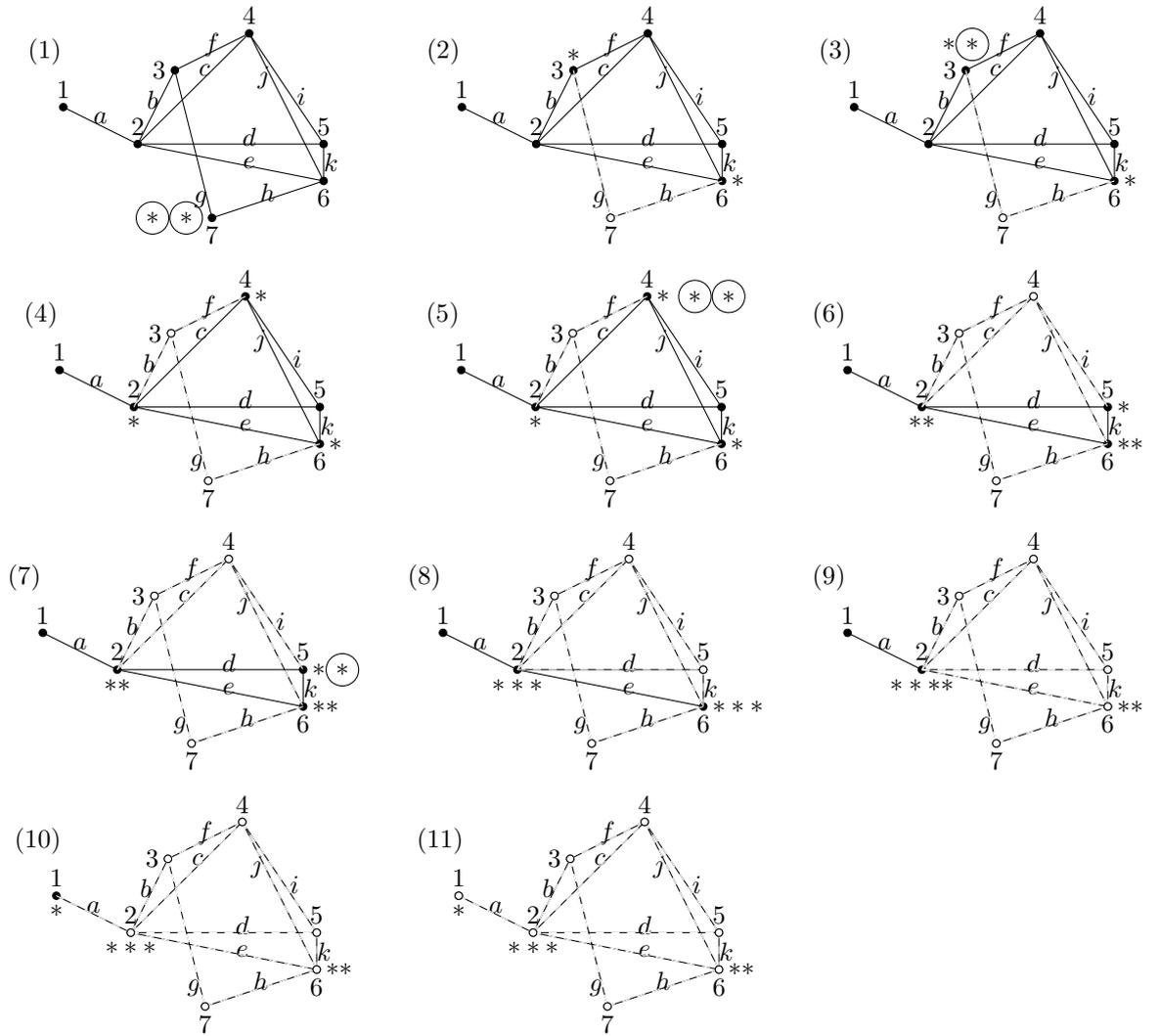


Figure 2: Example to illustrate the brushing strategy

$Z(L(K_n)) \leq 2B(K_n)$ (for $n \geq 3$) and by Equation 2, $Z(L(K_{1,n})) + 1 \leq 2B(K_{1,n})$ for all n . From these examples, one might also wonder if it is possible to bound $Z(L(G))$ from above by some multiple of $B(G)$. In what follows we construct a family of graphs to show that this is not the case.

Theorem 3.5. *There exists no real number c for which $Z(L(G)) \leq cB(G)$ for all graphs G .*

Proof. Consider the Cartesian product graph $P_r \square C_s$ where P_r is the path with r vertices and C_s is the cycle with s vertices. For what follows we represent $P_r \square C_s$ as the graph made up of r concentric s -cycles and $s(r-1)$ additional edges joining the corresponding vertices of the cycles. For an example with $r = 3$ and $s = 4$, see the first graph in Figure 3.

First we prove that $B(P_r \square C_s) \leq s + 2$. This is easy to establish by starting with $s + 2$ brushes at some vertex on the outermost concentric cycle of $P_r \square C_s$. Each time that a brush fires, if it has more brushes than incident dirty edges, then we send all excess brushes together to the nearest perimeter vertex in the clockwise direction. In Figure 3 we present the strategy on $P_3 \square C_4$, and note that this strategy easily generalizes for any $r \geq 1, s \geq 3$.

Next we prove that $Z(L(P_r \square C_s)) \geq r - 1$. $L(P_r \square C_s)$ can be represented as a graph that consists of $r - 1$ layers each having $2s$ vertices and $6s$ edges, except for the innermost layer which has $3s$ vertices and $6s$ edges. (For an example, see Figure 4). Now suppose that initially there is a layer k that has no black vertices. We may suppose that initially all other vertices are black. Unless layer k is the innermost layer, half of the vertices of layer k are adjacent to some vertex from a more central layer, and they can indeed be forced to black by those vertices. We note that these s vertices of layer k which are just forced to black are each adjacent to two of the remaining s (white) vertices of layer k , and hence they cannot force any of these white vertices to black. Similarly no vertex from any outside layer can force any of these s white vertices to black because any vertex from an outer layer is adjacent to either zero or two such white vertices. Therefore each layer of $L(P_r \square C_s)$ has to have at least one black vertex initially, and $Z(L(P_r \square C_s)) \geq r - 1$ follows.

So for any real number c and each $c' > c$ such that $c'(s + 2) + 2$ is a positive integer, $G = P_{c'(s+2)+2} \square C_s$ ($s \geq 3$ an integer) yields an example with $cB(G) < Z(L(G))$. \square

A similar result involving the more restricted brushing number $b(G)$ also holds:

Theorem 3.6. *There exists no real number c for which $Z(L(G)) \leq cb(G)$ for all graphs G .*

Proof. Consider the graph $\mathcal{G}_{k,6}$ that is obtained by taking k disjoint 6-cycles $\mathcal{C}_1, \mathcal{C}_2, \dots, \mathcal{C}_k$, each with vertices labelled 1 to 6 in cyclic order, and then, for each $i \in \{1, 2, \dots, k-1\}$, identifying vertex 4 of cycle \mathcal{C}_i with vertex 1 of cycle \mathcal{C}_{i+1} . The result is a connected graph with $k-1$ cut vertices, and $b(\mathcal{G}_{k,6}) = 2$ but $Z(L(\mathcal{G}_{k,6})) = k + 1$. Clearly the ratio $\frac{Z(L(\mathcal{G}_{k,6}))}{b(\mathcal{G}_{k,6})}$ grows without bound as k is allowed to increase. \square

We previously noted that the difference $B(G) - Z(G)$ can be arbitrarily large (and either positive or negative), depending on the choice of graph G . We note

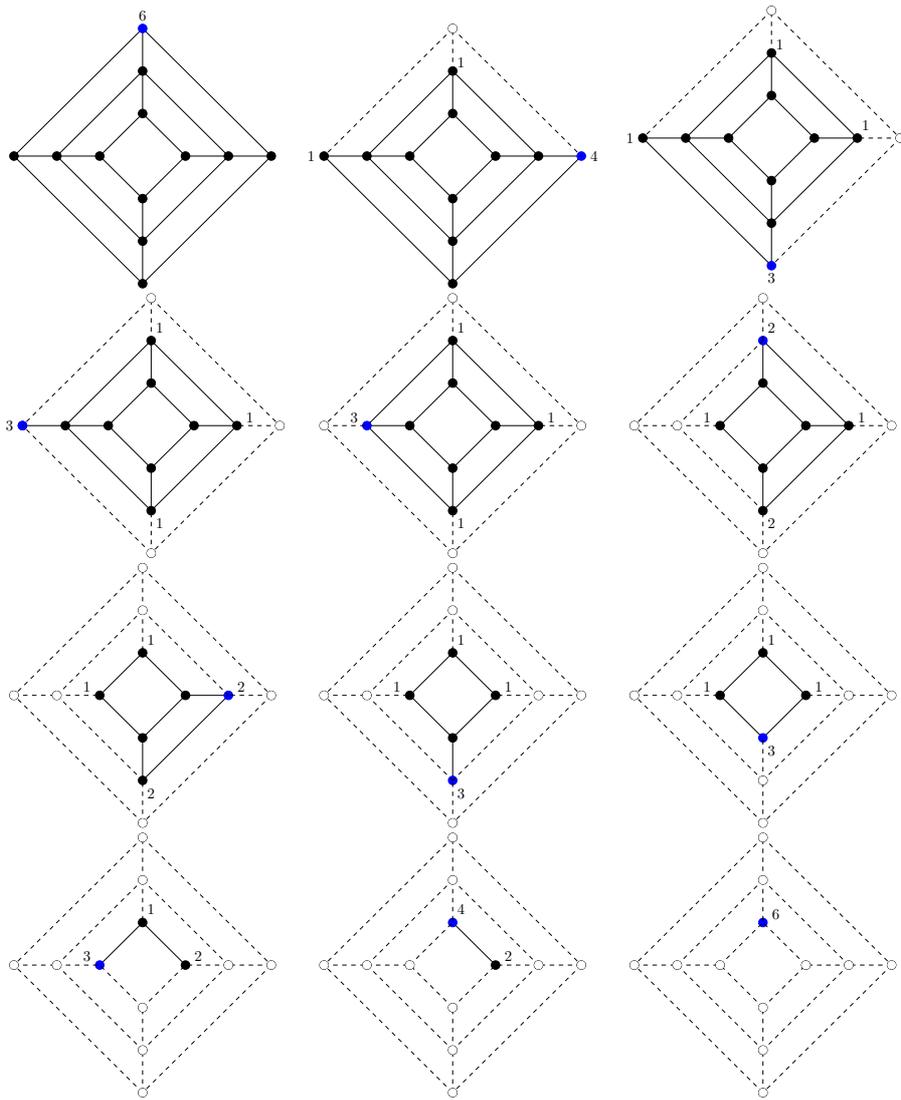


Figure 3: Brushing strategy for $P_3 \square C_4$

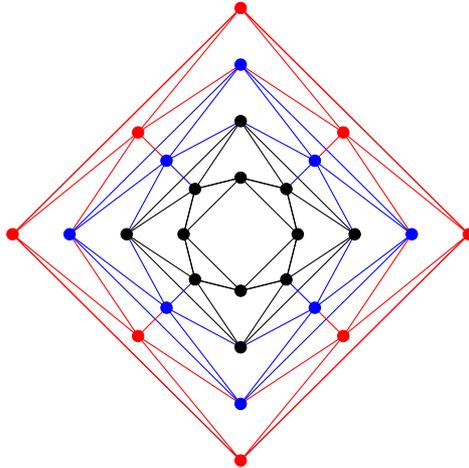


Figure 4: The three layers of $L(P_4 \square C_4)$

that this behaviour also occurs for line graphs. When considering the class of line graphs for $G = K_{1,n}$ we find that $B(L(G)) - Z(L(G))$ can be arbitrarily large and positive. For examples of line graphs for which $B(L(G)) - Z(L(G))$ can be arbitrarily large but negative, consider the graph $\mathcal{G}_{k,6}$ introduced in the proof of Theorem 3.6 and observe that $B(L(\mathcal{G}_{k,6})) = 4$ but $Z(L(\mathcal{G}_{k,6})) = k + 1$.

4 Zero-forcing number of a graph vs. the zero-forcing number of its line graph

It is known from [6] that $Z(G) \leq 2Z(L(G))$; each vertex in $L(G)$ that is in a zero-forcing set corresponds to an edge of G , where the set of endpoints for all of these edges is a zero-forcing set for G of size at most $2Z(L(G))$. In this section we use a zero-forcing set for $L(G)$ to construct a zero-forcing set for G of the same size, thus proving a conjecture in [6].

Theorem 4.1. *If G is a graph with no isolated vertices, then $Z(G) \leq Z(L(G))$.*

Proof. We will assume that G is connected, as this implies the stated result.

Let Z be a zero-forcing set for $L(G)$. Let $\mathcal{P}_1, \dots, \mathcal{P}_{|Z|}$ be the zero-forcing chains for a zero-forcing process starting with Z in $L(G)$ (using the notation in (3)). We order this collection so that any paths with just one vertex are at the end of this collection.

We will describe a strategy for choosing a zero-forcing set in G of size at most $|Z|$. At each step in the zero-forcing process on $L(G)$ we describe which vertices are added to a set S that will be a zero-forcing set for G . For each path in the zero-forcing chains at most one vertex in G will be added to S .

Suppose that at some point in the zero-forcing process on $L(G)$ $w_{i,j}$ is the active vertex; so $w_{i,j}$ forces $w_{i,j+1}$. At this step $w_{i,j}$ in $L(G)$ is black, as are all neighbours of $w_{i,j}$, except for $w_{i,j+1}$ (some of these neighbours might be initially black vertices of $L(G)$, while others may have been forced at some earlier step). In G consider the edges $w_{i,j} = \{a, b\}$ and $w_{i,j+1} = \{b, c\}$.

If $w_{i,j}$ is an initially black vertex in $L(G)$, then include a in S and mark the chain \mathcal{P}_i as used. At this step, add all the white vertices in $(N_G(a) \cup N_G(b)) \setminus \{a, b, c\}$ to S : each such white vertex is an endpoint of some edge in G with the property that the vertex in $L(G)$ corresponding to this edge is from an unused path. Mark each such path as used.

Then a forces b in G (if b is not black already), since at this step in G the only vertex adjacent to a that could possibly be white is b . At this point b can similarly force c (if c is not black already).

In both cases, $w_{i,j}$ zero forcing $w_{i,j+1}$ in $L(G)$ corresponds to some zero-forcing steps in G in which no white vertices are left incident with the edges $w_{i,j}$ and $w_{i,j+1}$.

Continue like this for all steps of the zero-forcing process on $L(G)$. If there are any unused chains left, then each of these chains must consist of a single vertex, which is initially black. If $w = \{a, b\}$ is such a vertex of $L(G)$, then at this step in $L(G)$ all neighbours of w are black; and any white vertex in $(N_G(a) \cup N_G(b)) \setminus \{a, b\}$ is an endpoint of some edge in G such that the vertex in $L(G)$ corresponding to this edge is from an unused path of length 1. Add all white vertices in $(N_G(a) \cup N_G(b)) \setminus \{a, b\}$ to S (each such vertex corresponds to an endpoint of some unused zero-forcing path of $L(G)$). If a is also black, then it forces b (if b is not black already) and vice versa. If both a and b are white then include one of them, say a , in S ; so a forces b . At this point each vertex of $L(G)$ is black as is every vertex in G . Thus this procedure produces a zero-forcing set for G of order at most $|Z| = Z(L(G))$. \square

We also have the following result which is parallel to Corollary 3.2.

Corollary 4.2. *For any graph G with k isolated vertices, $Z(G) \leq Z(L(G)) + k$.*

5 Brushing number of a graph vs. the brushing number of its line graph

Finally we prove that $B(G) \leq B(L(G))$ for any graph G with no isolated vertices.

Theorem 5.1. *For any graph G with no isolated vertices, $B(G) \leq B(L(G))$.*

Proof. As in the previous theorems, we can assume that G is connected. Further, the theorem holds if G is a single edge, so we can also assume that $L(G)$ is not a single vertex.

Consider a brushing configuration $\mathcal{B}_{L(G)}$ of $L(G)$ with $B(L(G))$ brushes. In this brushing configuration assume that the vertices fire in order $v_1, v_2, \dots, v_{|V(L(G))|}$. Using this ordering of $\mathcal{B}_{L(G)}$ we will choose an initial placement of at most $B(L(G))$ brushes at the vertices of G to construct a brushing configuration \mathcal{B}_G of G .

We consider two types of vertices in $L(G)$. The first, called *type 1*, is the set of vertices that are not incident to any clean edges when they fire in $\mathcal{B}_{L(G)}$. The second set, called *type 2*, are the remaining vertices, so these vertices have at least one incident clean edge when they fire in $\mathcal{B}_{L(G)}$. Clearly the first vertex to fire, v_1 , is a type 1 vertex.

Assume that in the brushing process vertex v fires. If v is type 1, then there must be at least $\deg_{L(G)}(v)$ brushes at v in $L(G)$ in the initial configuration of brushes in $\mathcal{B}_{L(G)}$ (since no edges incident with v are clean, no new brushes have been sent to v). Consider the edge $v = \{a, b\}$ in G . Note that $\deg_{L(G)}(v) = \deg_G(a) + \deg_G(b) - 2$ and we will assume that $\deg_G(a) \geq \deg_G(b)$.

Since G is not a single edge $\deg_G(a) \geq 2$. Put $\deg_G(a) - s - 2$ brushes at a where s is the current number of clean edges incident with a in G . Similarly, put $\deg_{L(G)}(v) - (\deg_G(a) - s - 2) - t$ brushes at b where t is the current number of clean edges incident with b in G . Note that $\deg_{L(G)}(v) - (\deg_G(a) - s - 2) - t$ is the current number of unclean edges at b in G . So b fires and cleans the edge v (and possibly some other edges in G), and therefore a brush is sent from b to a . This reduces the number of unclean edges incident with a by 1 and increases the current number of brushes at a from $\deg_G(a) - s - 2$ to $\deg_G(a) - s - 1$. So there are as many brushes at a as the number of unclean edges incident with a , and hence a fires in G .

Suppose that $v = \{a, b\}$ is the first vertex in $v_1, v_2, \dots, v_{|V(L(G))|}$ of type 2. Let p be the number of clean edges incident with v in $L(G)$ just before v fires. Then there must be at least $\deg_{L(G)}(v) - 2p$ brushes at v in $L(G)$ in the initial configuration of brushes in $\mathcal{B}_{L(G)}$ (the number of dirty edges incident with v is $\deg_{L(G)}(v) - p$ and (at least) p brushes were sent to v when the incident edges were cleaned).

Our aim is to show that both vertices a and b in G can fire (if they have not fired yet) after distributing at most $\deg_{L(G)}(v) - 2p$ brushes among them. Any vertex u that fires before v in $\mathcal{B}_{L(G)}$ must be of type 1, and the brushing strategy for type 1 vertices guarantees that both endpoints of the edge u in G have already fired. So any clean edge $\{v, x\}$ in $L(G)$ has been cleaned because of the firing of the vertex x in $L(G)$ at some earlier step, and so both endpoints of the edge x in G must have already fired cleaning one of the endpoints, say a , of the edge $v = \{a, b\}$ in G and the edge v itself. Put (at most) $\deg_{L(G)}(v) - 2p$ brushes at b in G , and so b can fire.

Consider the next vertex of type 2 in $\mathcal{B}_{L(G)}$. Note that each time a vertex v in $L(G)$ of type 2 with an incident clean edge $\{v, w\}$ is considered in $\mathcal{B}_{L(G)}$, it must be that in G both endpoints of the edge w have already fired. Denote the edge v in G as $\{a, b\}$. Since $v \cap w \neq \emptyset$ in G , this means that either a or b has already fired and cleaned the edge v in G . The degree arguments in the preceding paragraph can be repeated to show that the other endpoint of v in G also fires after putting the corresponding number of brushes there. This procedure can be repeated until all type 2 vertices in $\mathcal{B}_{L(G)}$ have been considered.

It is now easy to see that we have established a distribution of at most $B(L(G))$ brushes among the vertices of G which cleans all edges and vertices of G . \square

We state the following result which has essentially the same proof as Corollary 3.2.

Corollary 5.2. *For any graph G with k isolated vertices, $B(G) \leq B(L(G)) + k$.*

We remark that this method also works for the variant of brushing that considers capacity constraints, as in the setting of [2, 5, 14] and as in the proof

of Theorem 5.1. In particular, the construction in Theorem 5.1 can be used to prove the following corollary.

Corollary 5.3. *For any graph G with no isolated vertices, $b(G) \leq b(L(G))$.*

Similar to Corollary 5.2, we obtain the following result.

Corollary 5.4. *For any graph G with k isolated vertices, $b(G) \leq b(L(G)) + k$.*

6 Further Work

The inequalities of Theorems 3.1, 4.1 and 5.1 are all tight when $G = C_n$ with $n \geq 3$ and when $G = P_n$ with $n \geq 2$. We also note that the graphs $\mathcal{G}_{k,6}$ from Theorem 3.6 yield a family of examples with equality for Theorem 4.1 (as does any natural generalization with arbitrary cycle lengths). It would be interesting to know what other classes of graphs cause these bounds to hold with equality.

An algebraic property of the zero-forcing number is that it is bounded below by the maximum nullity of the graph (as defined in [1]). Indeed, it was this property that initially motivated the study of zero forcing. It would be interesting to try to connect the maximum nullity of $L(G)$, or some other algebraic property of $L(G)$, to $B(G)$.

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